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Research and Development Technical Report
SLCET-TR-92-3

# Frequency Trimming Technique for Surface Acoustic Wave Devices

Raymond McGowan, John Kosinski, Jeffrey Himmel,
Richard Piekarz, Theodore Lukaszek, and Robert Zeto
Electronics Technology and Devices Laboratory

June 1992



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# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188



1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
June 1992

3. REPORT TYPE AND DATES COVERED
Technical Report

4. TITLE AND SUBTITLE
FREQUENCY TRIMMING TECHNIQUE FOR SURFACE ACOUSTIC WAVE DEVICES

5. FUNDING NUMBERS

6. AUTHOR(S)
Raymond McGowan, John Kosinski, Jeffrey Himmel, Richard Piekarz, Theodore Lukaszek, and Robert Zeto

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Laboratory Command (LABCOM)
Electronics Technology and Devices Laboratory (ETDL)
ATTN: SLCET-MA-A
Fort Monmouth, NJ 07703-5601

8. PERFORMING ORGANIZATION REPORT NUMBER
SLCET-TR-92-3

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
Currently, there is an in-house effort to produce a vibration-insensitive surface acoustic wave (SAW) resonator to stabilize the outputs of state-of-the-art SAW oscillators. One of the key elements in this investigation is the development of a simple, yet sensitive frequency trimming procedure to adjust the resonator frequency of a fabricated device. Background and procedural information for performing frequency trimming on a SAW resonator using a wet isotropic chemical etch are provided in this report. The results of this study revealed a trimming sensitivity of 0.33 ppm/A and 11.4% of performance degradation for a 10 kHz or 100 ppm shift in the resonant frequency of a device.

14. SUBJECT TERMS
Surface Acoustic Wave Devices; Wet Chemical Processing; Frequency Trimming; Etch-Rate Study

15. NUMBER OF PAGES
38

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | UL |

CONTENTS

## FIGURES

## TABLES

## INTRODUCTION

An on-going in-house research project to improve the state-of-the-art for vibration insensitive surface acoustic wave (SAW) stabilized oscillators has created the need for a complete in-house design, fabrication and evaluation facility for SAW resonators. This is essential because all aspects of the resonator's design must be controllable to optimize its vibration characteristics. One of the keys to this effort is the post-fabrication processing which is nearly always required to move the resonance frequency of the device to the desired frequency of operation. Background information and processing techniques for precise frequency trimming of a SAW resonator using a wet isotropic chemical etch are provided in the following report.

## BACKGROUND

Surface acoustic wave (SAW) stabilized oscillator technology has become an area of interest to many designers of avionic, radar and military communication systems as the operating frequencies of these systems increase and the performance characteristics of SAW devices improve over time. Several key determinants have led to this current interest in SAW devices. The first factor influencing this interest in SAW technology is the wide range of fundamental frequencies achievable using this technology. SAW devices have a fundamental frequency of operation which ranges from 50 MHz to 2000 MHz. Second, these devices are planar and inherently rugged, which are two important factors for most electronic military systems. Third, SAW device technology is able to capitalize on the advances in processing and packaging technology developed for bulk acoustic wave (BAW) devices which is a more mature technology. Lastly, SAW device fabrication is relatively easy and compatible with most standard microelectronic processing techniques.

The advancement of electronic military systems has placed extremely stringent tolerances on the performance of many of the components and subsystems used in them. One current military system specification for a SAW oscillator requires that the operating frequency of the device not change by more than 280 parts/million (ppm) due to all causes of frequency drift over an expected operational lifetime of 10 years. Some common causes of frequency drift in a SAW oscillator are temperature fluctuations, vibration and aging.

Once the system requirements for a SAW oscillator are known, the next logical topic of discussion is the frequency control element of the oscillator: the SAW resonator. In particular, the discussion will concentrate on how the fabrication of the SAW resonator affects the overall frequency accuracy of the SAW oscillator. Under the best fabrication conditions available, the initial on-set frequency of a SAW resonator is typically ±200 to ±500 ppm from the desired frequency. This wide range in resonant frequency is due in large part to a lack of precise control over processing variables such as metallization thickness, accurate

alignment of the device with the substrate, electrode-to-gap variations caused by uncompensated isotropic wet chemical etch processes, etc. Resonant frequency variations are also caused by substrate-to-substrate variations, i.e., angle of crystal cut. [1]

The most common technique for overcoming these initial resonant frequency deviations is to employ a frequency trimming process. In most cases, reactive ion etching (RIE) with $CF_4$ is used to trim the center frequency of a SAW resonator. Frequency trimming using this technique is quite accurate; for example, a 465 MHz SAW reported by Parker and Montress showed a frequency tunability of -3 to -6 ppm/Å. It should be noted from the negative sign in the frequency tuning parameter that the RIE technique is unidirectional and lowers the frequency of the device being processed. This occurs because RIE with $CF_4$ etches quartz approximately seven times faster than aluminum, therefore the aluminum transducers and grating structures serve as a mask and allow the quartz between the aluminum structures to be removed. Effectively, this process increases the discontinuity of the surface structures, which, in turn, lowers the velocity of the traveling surface wave and the detected output frequency.

In contrast to the RIE process, the isotropic chemical etch effects change in the resonant frequency of a device by reducing the mass of the aluminum transducers and grating on the active surface of the SAW substrate. This technique is also unidirectional but it allows the upward tuning of the device's center frequency. The results of this study show that for small shifts in center frequency, device performance is not adversely effected by wet chemical etching.

**ETCH RATE STUDY TO DETERMINE FREQUENCY TRIMMING TECHNIQUES**

The first step in performing an etch rate study was to select the most appropriate etchant for the task. In this particular situation, the ideal etchant should have a slow etch rate, 20-50 Å/min, when used at room temperature and should serve as a polishing etch. Based on the desired etchant characteristics and available candidates [2], the aluminum etch chosen was a commercially prepared solution composed of phosphoric acid, acetic acid, nitric acid and deionized water. This solution will be used in an immersion etching scheme where the device being processed is submerged in the etchant for a specified period of time resulting in the removal of a predetermined thickness of aluminum.

Although it is not required, the following procedures were carried out in a class 10/100 cleanroom. The requisite equipment for the etch rate study was as follows:

1. Fume hood
2. Hot plate with digital temperature readout
3. Deionized water rinse bath
4. Alpha-Step thickness measuring tool

5. Process timer
6. 1000 ml teflon container
7. 500 ml graduated cylinder
8. 100 ml graduated cylinder
9. Sponge swabs

The chemical and material supplies needed were as follows:

1. 3" Si wafer coated with 1200 Å of aluminum
2. Positive photoresist
3. Acetone
4. Isopropanol
5. Deionized water
6. Aluminum etch (16 parts phosphoric acid : 1 part acetic acid : 1 part nitric acid : 2 parts deionized water)
7. Dry nitrogen

Since the manufacturer did not provide etch rate information for the aluminum etch, the first task is to determine the etch rate of the concentrated solution. First, the aluminized 3" silicon wafer had to be prepared for the upcoming tests. A set of simple rectangular test patterns was placed on the wafer using the following procedure:

1. The wafer was rinsed with deionized water and dried with a nitrogen blower.

2. Using a sponge swab, several rectangular areas were masked off on the aluminum surface of the wafer with photoresist.

3. The coated wafer was then placed on the hot plate, which was set at a temperature of 105°C for 1 minute.

4. The wafer was then submerged in the aluminum etch until only the rectangular test patterns remained on the wafer.

5. The photoresist was then removed using acetone and the wafer was then cleaned with isopropanol and deionized water and dried with nitrogen.

With the test patterns formed on the surface, the metal thickness is measured at the five test points indicated in Figure 1. The average aluminum thickness was determined to be 1200 ±100 Å. It should be noted that the resolution of the Alpha-Step measuring tool is ±50 Å. Figure 2 is a sample Alpha-Step measurement showing the initial thickness profile of the aluminum at reference point 1 in Figure 1.

Now that the preliminary work has been completed, the etch rate can be determined for the undiluted etchant. The procedure for determining the etch rate of a given solution is as follows:

1. Using an appropriate application tool, apply photoresist to all areas of the test pattern leaving only the desired

test area exposed.

2. Place the wafer on the hot plate, which should have a nominal temperature of 105°C, for 1 minute, to harden the photoresist so it serves as a mask during the following etch process.

3. With the wafer in a holder, submerge the wafer into the etch bath for a specified period of time. (For the purposes of this study, the etch bath consists of 500 to 600 ml of the aluminum etch at a given concentration in a 1000 ml teflon container. The etch times ranged from 1 minute to 2 minutes.)

4. Once the wafer is removed from the etch bath, it is placed in the deionized water rinse for approximately four minutes to insure that the etch process has stopped.

5. The next step is to remove the photoresist mask with acetone and clean the substrate with isopropanol, deionized water, and dry nitrogen.

6. Lastly, the sample is placed on the stage of the Alpha-Step system and the etched aluminum-silicon boundary is measured.

The etch rate of the undiluted solution is determined by performing three one-minute etches on the test pattern. The exposed area of the test pattern is increased for each iteration, creating a terraced effect on the aluminum strip. Figure 3 shows the aluminum profile for the test pattern created after the first one-minute etch.

Figures 3 and 4 show the aluminum profile of the first terrace created on the test pattern after the first and second one-minute etches. Figure 5 shows the aluminum profile for the second terrace created after the third one-minute etch. A summary picture of the test pattern profiles is given in Figure 6. Using the data from Figures 2-5, it can be easily determined that the etch rate of the undiluted aluminum etch is 400 ±50 Å/min. This was determined by taking an average of the three etch rates which were 400 Å/min, 450 Å/min and 350 Å/min, respectively.

Now that the etch rate of the undiluted solution is known, the aluminum etch must be diluted to achieve the desired etch rate of 20-50 Å/min. Following the procedure for determining the etch rate of the original etchant, the etch rates for various concentrations of the aluminum etch were measured; the results are listed in Table 1. The concentration selected for further evaluation was the 9.1 : 1 solution (composed of 500 ml of deionized water : 55 ml of aluminum etch), because of the slow etch rate of 25 Å/min and superb post-etch surface quality.

Before an actual device can be processed, the etch rate of the solution has to be known as a function of time because it

will take a significant amount of time for the diluted etchant to dissolve the native oxide, $Al_2O_3$, and begin to etch the aluminum. In an attempt to simulate the actual processing of a SAW resonator, an inoperative device was used with a nominal metal thickness of 3000 Å. It is desired to have the thickness of the metal reduced uniformly across the device, therefore, masking of the surface is not required; leaving the following simplified procedure:

1. Place the device in an appropriate holder and submerge the device in the etchant for a specified length of time. (The time intervals used were 2, 4, 6 and 8 minutes.)

2. Remove the device from the etchant and place it in the deionized water rinse for approximately 4 minutes.

3. Once the deionized water rinse is completed, the device is dried with nitrogen and the metal thickness is measured using the Alpha-Step.

4. In order to obtain the most accurate data of the surface etch over the whole device, readings were taken at the four reference points labeled on Figure 7.

The results of the etch rate vs. duration study are listed in Table 2 and shown on Figure 8. These results clearly show that the thin oxide layer severely impedes the etching of the transducer. Therefore, as a function of time, the etch rate of the solution triples as the etch time increases from 2 minutes to 8 minutes with a very sharp transition at the 5 minute mark, as seen in Figure 8.

## EVALUATION OF FREQUENCY TRIMMING PROCEDURE

### Equipment and Material Requirements

Completion of the etch rate study allows the start of the primary thrust of this investigation: device processing and evaluation using the wet chemical etch technique. The devices used to evaluate the wet chemical frequency trimming technique were 100 MHz two-port SAW resonators designed and fabricated in-house. The equipment and materials required for the evaluation of the SAW resonators are as follows:

1. Hewlett Packard (HP) 8753B Network Analyzer
2. HP 9000 Series 300 Controller
3. HP 9876A Thermal Printer
4. HP 7475A Plotter
5. HP 85160A S-Parameter Evaluation Software
6. HP 85165A Equivalent Circuit Evaluation Software
7. Test Fixture
8. Rubber Cement (Acoustic Absorber)

### Statement of Problem

Two problems are addressed with this frequency trimming experimentation. First (given that the resonator is lower in frequency than the desired operational frequency), what etch times are required to move the resonance frequency a specified amount? Second, after the device has been processed, what degree of performance degradation results from this processing? To begin the analysis, a frequency shift of 10 kHz or 100 ppm was selected as a target for the experiment. Therefore, using the theoretical expressions found in Gerber and Ballato [3] for the grating frequency and the initial data from the device chosen to test the process, approximately 200 Å of aluminum would have to be removed from the transducers and grating structures to bring about this frequency shift. However, realizing that the initial oxide thickness of the device would be much thicker than that of a recently processed device, a 6-minute etch time was chosen for the initial etch as compared to the 4.5-minute etch time prescribed by Figure 8.

Before the resonator was processed the initial performance of the device was measured; the results can be seen in Figures 9-12. Figure 9 shows the fundamental node of the sin x/x frequency response of the transducer combined with the peak grating response. Figure 10 shows an expanded view of the peak grating response in the amplitude-frequency domain. Figure 11 shows the phase vs. frequency response over the 500 kHz region around the center frequency. Lastly, Figure 12 provides the equivalent circuit data for the unprocessed resonator.

<u>Procedure for Resonator Performance Evaluation</u>

Once the initial data are obtained, the wirebonds are removed from the device and the initial metal thickness is measured; see Table 3. Next the resonator is processed using the same procedure developed for the inoperative device. Once the device has been processed and the aluminum profile measured on the Alpha-Step (see Table 3), the procedure for the device performance evaluation is as follows:

1. Wirebonds are attached to the busbar of the device and the device is then soldered into the test fixture.

2. The HP controller, network analyzer, and peripherals are turned on and the S-parameter software is loaded into the controller.

3. The test fixture with the attached resonator is connected to the network analyzer.

4. Following the software prompts, one is led through the S-parameter measurements and data acquisition, and the resonance frequency of the device is noted.

5. Once all the S-parameter data are obtained the equivalent circuit software is loaded into the HP controller.

6. In setting up the measurement using the equivalent circuit software, the resonance frequency obtained from the S-parameter evaluation is used to bypass the resonance frequency and nominal Q search, which speeds up the measurement significantly.

7. Again following the softkey menu, the measurement can be set up and performed and the output data can be obtained.

Figures 13-16 show the S-parameter and equivalent circuit data for the resonator after the first etch. Comparing Figures 10 and 14, it can be seen that the peak response shifted up in frequency about 12 kHz. This information can also be obtained from the phase vs. frequency plots (seen in Figures 11 and 15), by noting the difference in the zero crossing for the odd frequency response, distinguished by its sharp phase transition from -180° to +180° in the phase-frequency domain. Figure 16 provides a listing of the equivalent circuit parameters for the etched device, and, when it is compared to the data in Figure 12 for the initial device, it confirms the results obtained from visual inspection of the $S_{21}$ magnitude and phase plots.

A second etch was performed on the device, this time the goal was to remove the minimum measurable thickness approximately 50 Å and measure the frequency shift caused by the etch. Applying the etch rate data from Figure 8, an etch time of two minutes was selected for processing the device. (The aluminum profile data from the Alpha-Step measurements, after the second etch, are in Table 3). Then, using the resonator parameter evaluation procedures established previously, the S-parameter and equivalent circuit data can be obtained, as seen in Figures 17-20. Further analysis of the results will be discussed in the conclusions.

**SUMMARY AND CONCLUSIONS**

Table 4 provides a summary of the resonator parameters for the initial device and the two post-etch states. The following list describes the terms in Table 4:

- $f_s$ - the dominant resonant frequency of the resonator.
- $f_{g-}$ - the lower frequency at which the reflection band minimum occurs.
- $f_{g+}$ - the upper frequency at which the reflection band minimum occurs.
- $f_{g,avg}$ - the frequency calculated by taking the average of $f_{g-}$ and $f_{g+}$; it represents the frequency of peak reflection for the grating array.

- RBW - the reflection bandwidth is the bandwidth between the grating band minima.

- $f_{long}$ - the separation between longitudinal cavity modes determined empirically by measuring the difference between the even and odd frequency responses that appear in the reflection bandwidth.

- $f_{S21,max}$ - the frequency where the maximum amplitude response occurred for $S_{21}$.

- $|S_{21}|_{max}$ - the maximum amplitude of the resonator response.

- $t_{Al}$ - the measured metal thickness.

- $r_{cal}$ - the calculated reflection coefficient of a single grating, based on metallization thickness.

- $R_1$ - the resistor value in the equivalent resonant circuit.

- $Q_l$ - the loaded quality factor of the resonator.

- $Q_u$ - the unloaded quality factor of the resonator.

- Etch Time - the length of time that the resonator was exposed to the etchant.

- Etch Rate - the amount or thickness of aluminum removed from the surface per unit time.

- Trim Rate - the shift in frequency caused by the removal of a unit thickness of surface metallization.

The unloaded Q is of great importance because $Q_u$ multiplied by the resonance frequency of the resonator gives the device's figure of merit. $(Q_u*f_s)_{max}$ is $1.05*10^{13}$ and is the material limited figure of merit. $Q_u*f_s$ for the original device is 18.4% of the material limit. The initial processing reduced the $Q_u*f_s$ product to 16.0% of the material limit which corresponds to a 2.4% reduction in the absolute performance of the device or a 13% degradation in comparison to the original device. Unfortunately, the second etch led to a dramatic degradation in device performance with the $Q_u*f_s$ product dropping to 11.9%, which represents a 35% degradation in figure of merit in comparison to the original device. It is interesting to note that for the intended 10 kHz shift, assuming that the unloaded Q decreases

linearly with frequency shift, an 11.4% performance degradation would result when compared to the original device.

The dominant resonant peak for this device is an odd frequency response, which is given by $f_s$ in Table 4. Provided that the initial metal thickness is given for each of the three states, the trim rate for the device can be determined. The trim rate or trimming sensitivity is defined as the change in resonance frequency divided by the change in metal thickness; and a trim rate of 33.04 Hz/Å and 32.82 Hz/Å is obtained going from the initial state to the first etch state and then from the first etch state to the second etch state, respectively. Similar devices would have an average trimming sensitivity of +32.9 Hz/Å or +0.33 ppm/Å, and, assuming that a minimum etch time of 1 minute is used, the minimum frequency tuning capability of this technique would be approximately 800 Hz.

**ACKNOWLEDGMENTS**

The authors would like to thank the Microcircuit Packaging Team for their invaluable assistance during this investigation. In particular, the authors would like to thank Ed Baidy and Drew Brocking for dicing the SAW devices and bonding all the SAW substrates into the test fixture.

**REFERENCES**

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3. W.R. Shreve and P.S. Cross, "Surface Acoustic Waves and Resonators," in Precision Frequency Control, Vol. 1, Acoustic Resonators and Filters, Chap. 2, E.A. Gerber and A. Ballato, Eds., Orlando: Academic Press, Inc. 1985, pp. 119-145.

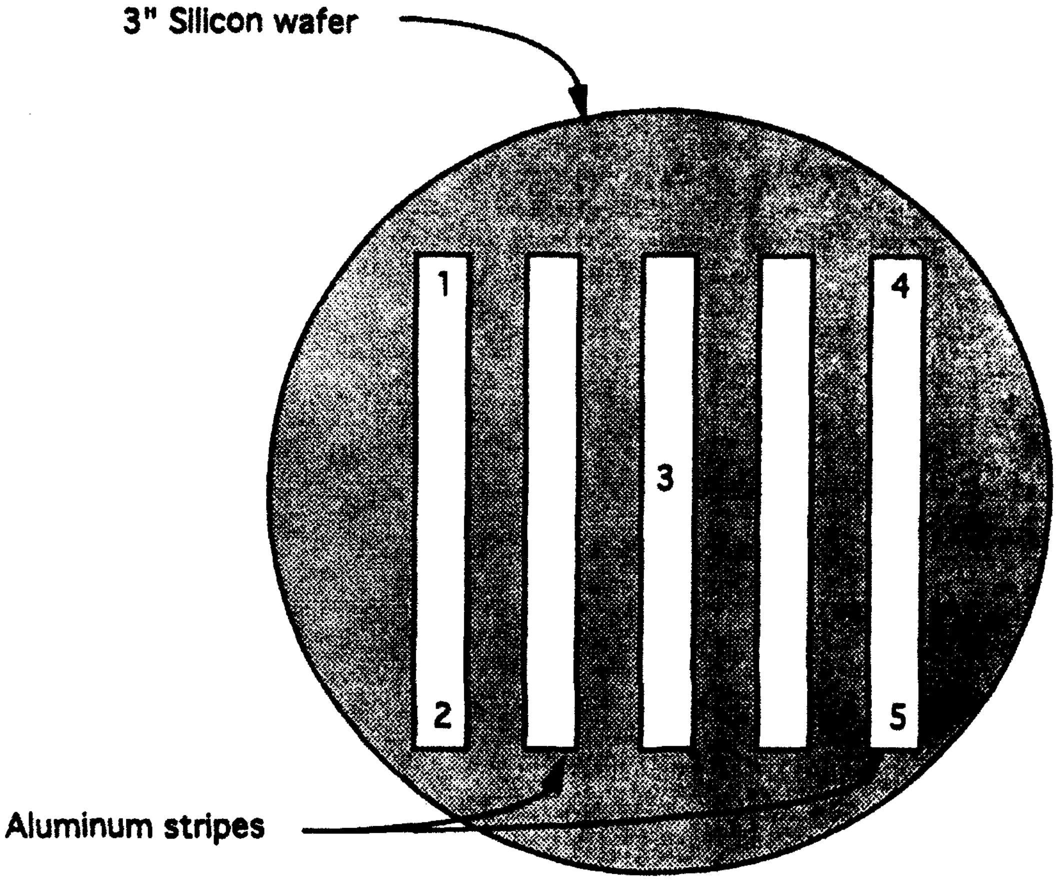


**Figure 1. Configuration of the Test Pattern**

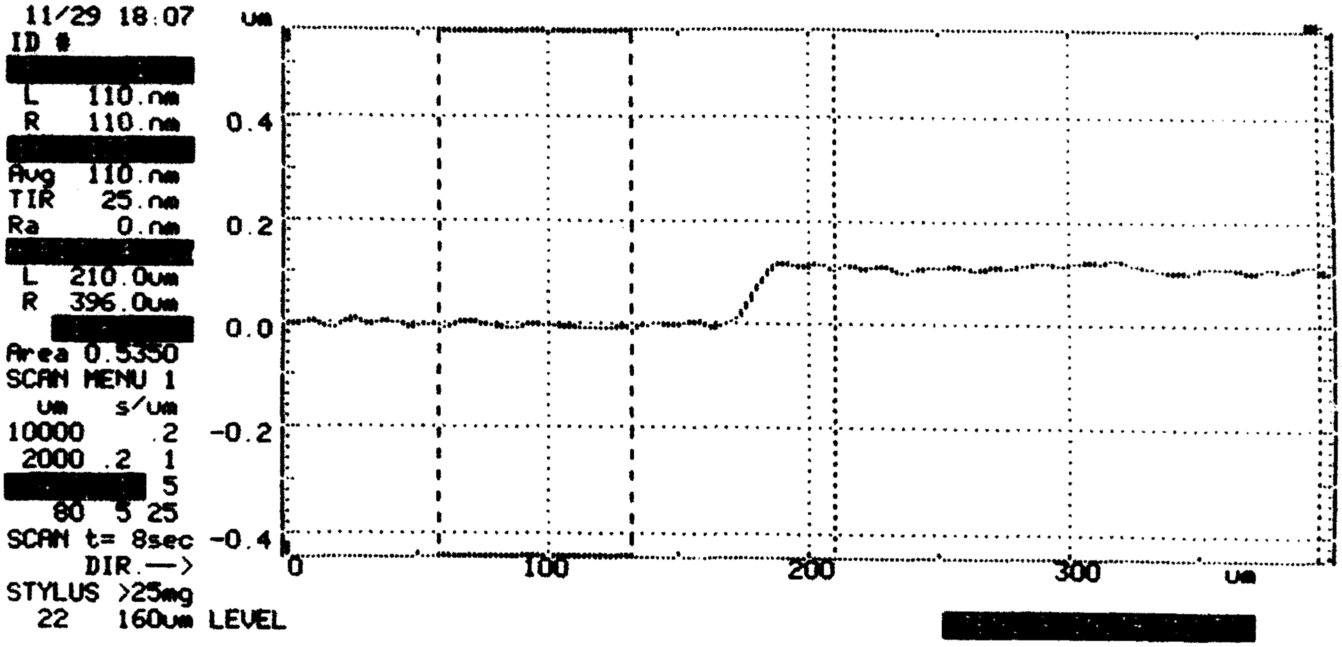


Figure 2. Alpha-Step Profile of the Original Surface

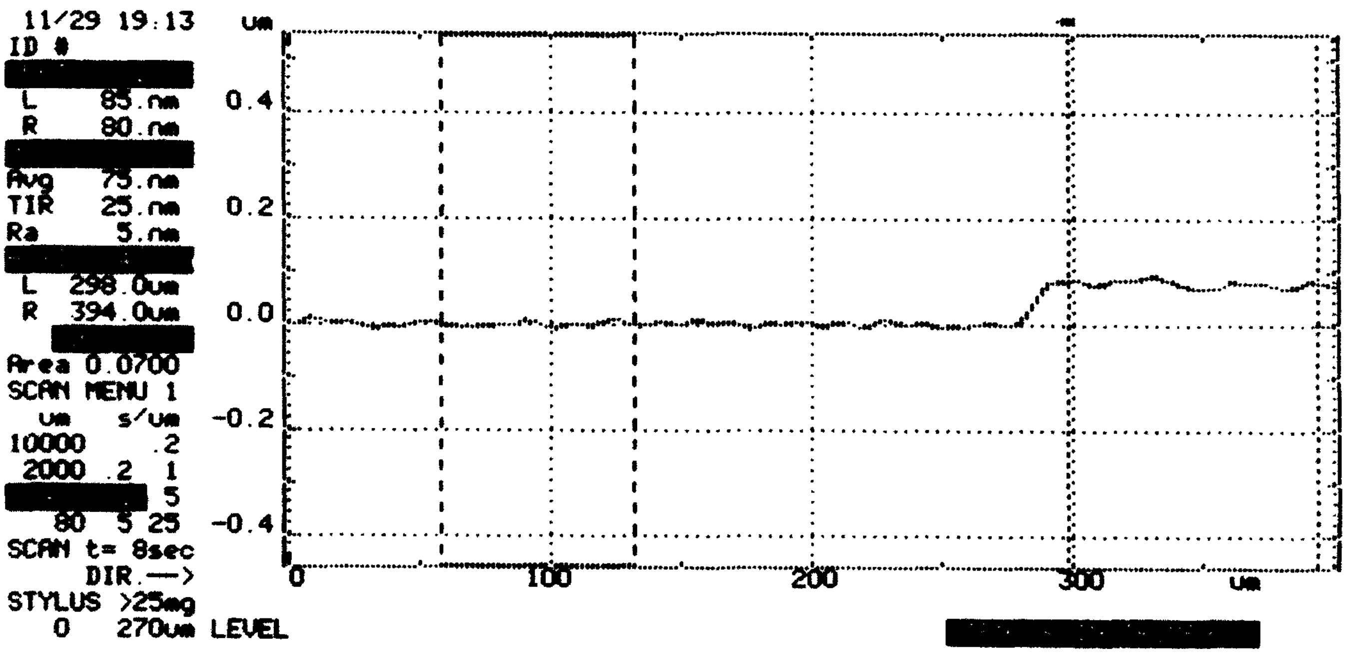


Figure 3. Alpha-Step Profile of First Terrace After One-Minute Etch

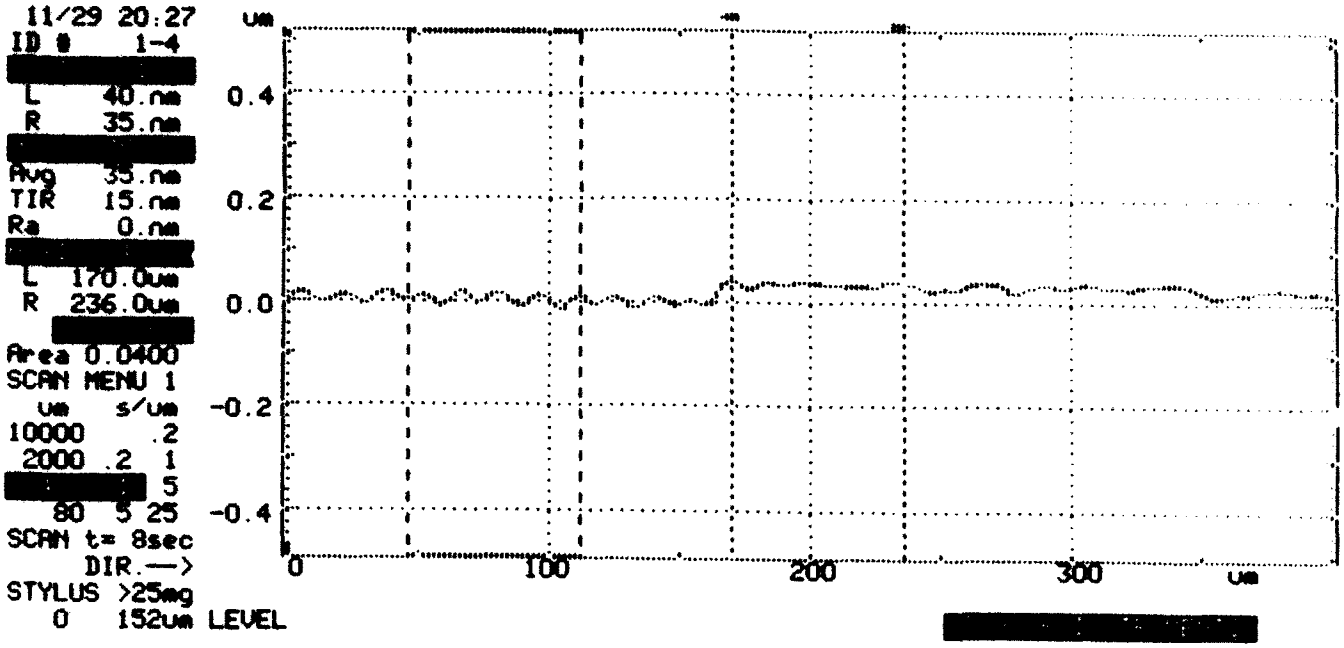


**Figure 4. Alpha-Step Profile of First Terrace After Second One-Minute Etch**

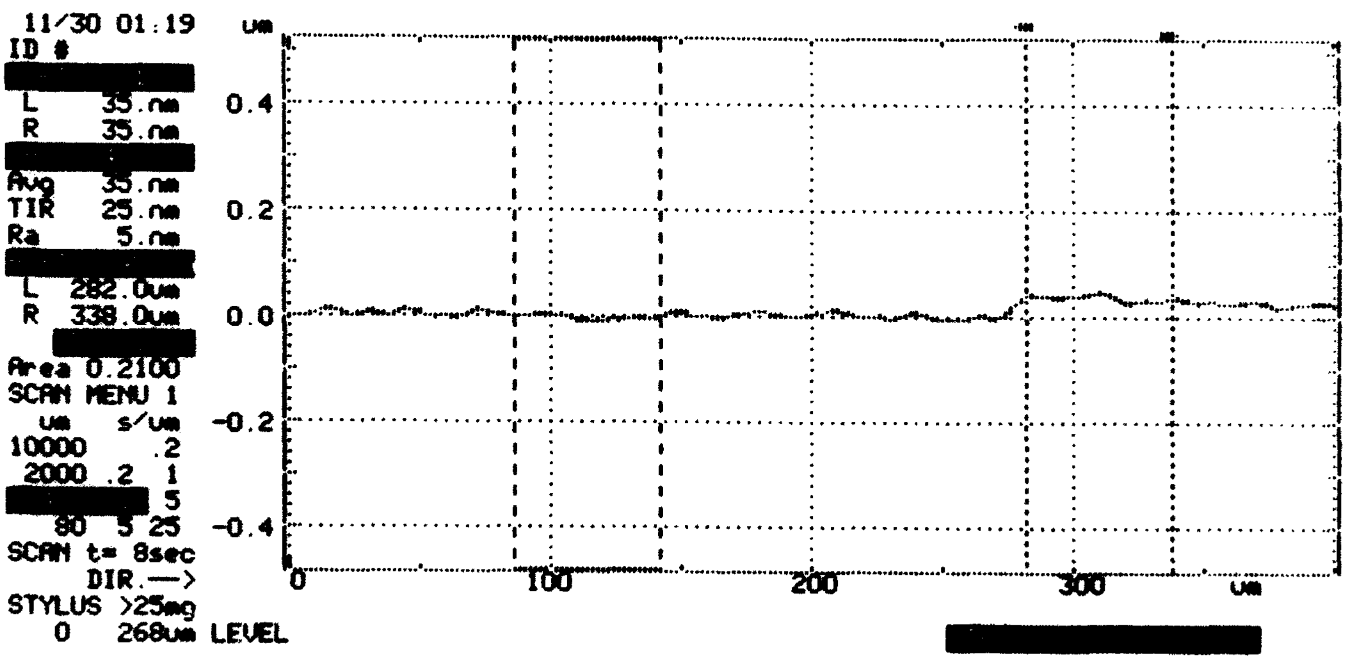


**Figure 5. Alpha-Step Profile of Second Terrace After Third One-Minute Etch**

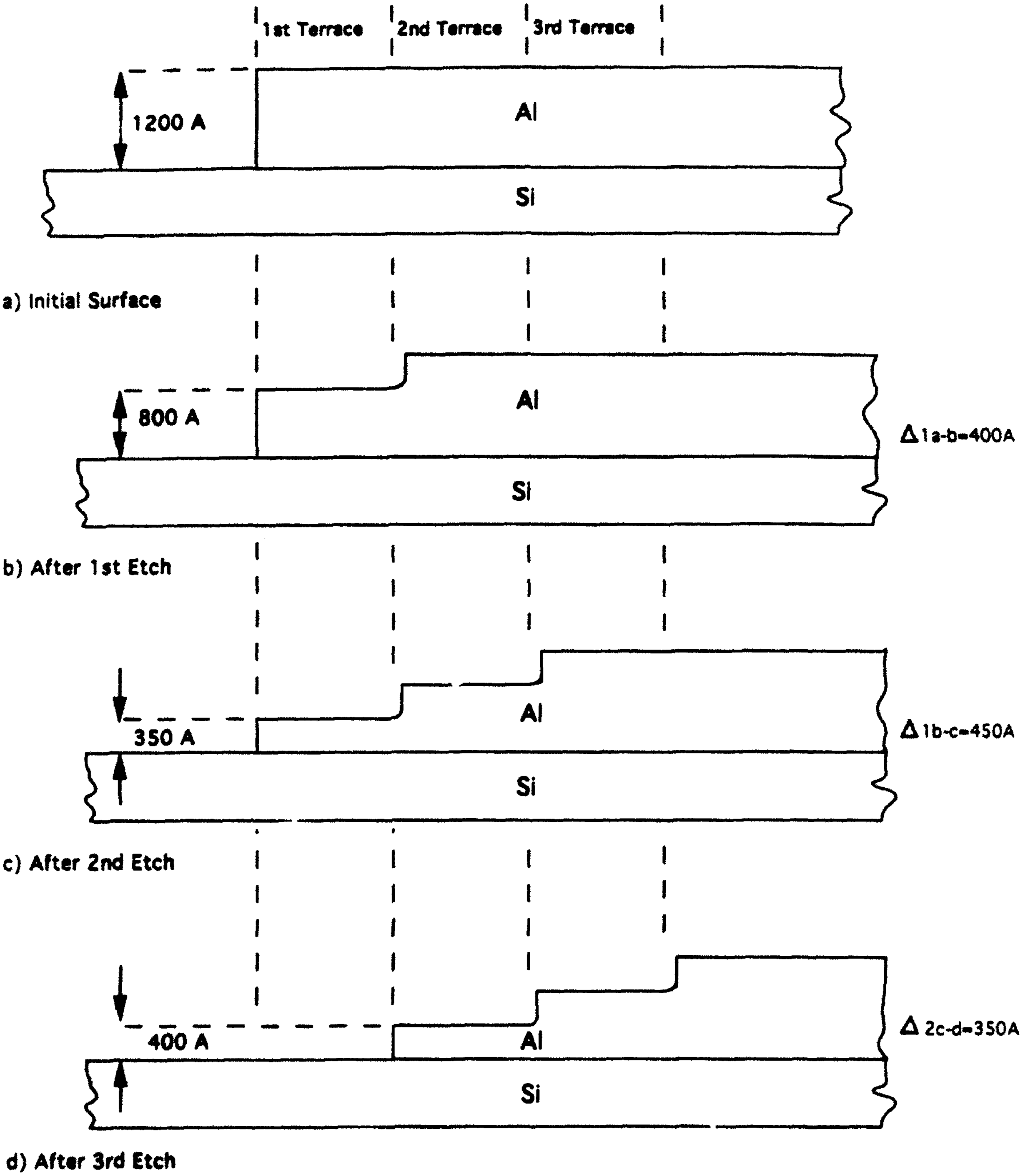


**Figure 6. Profile of the Aluminum Test Pattern**

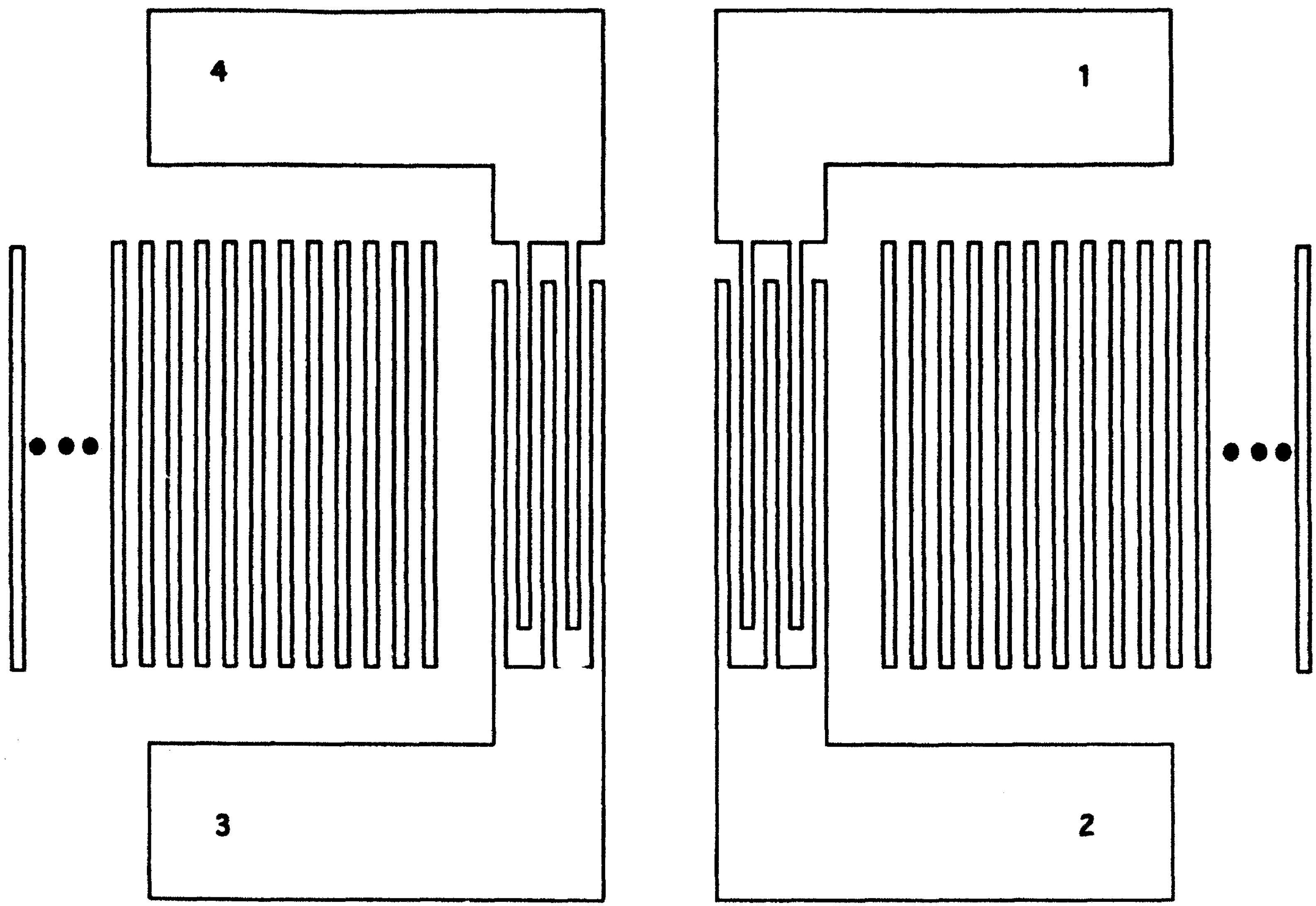


Figure 7. Two - Port SAW Device

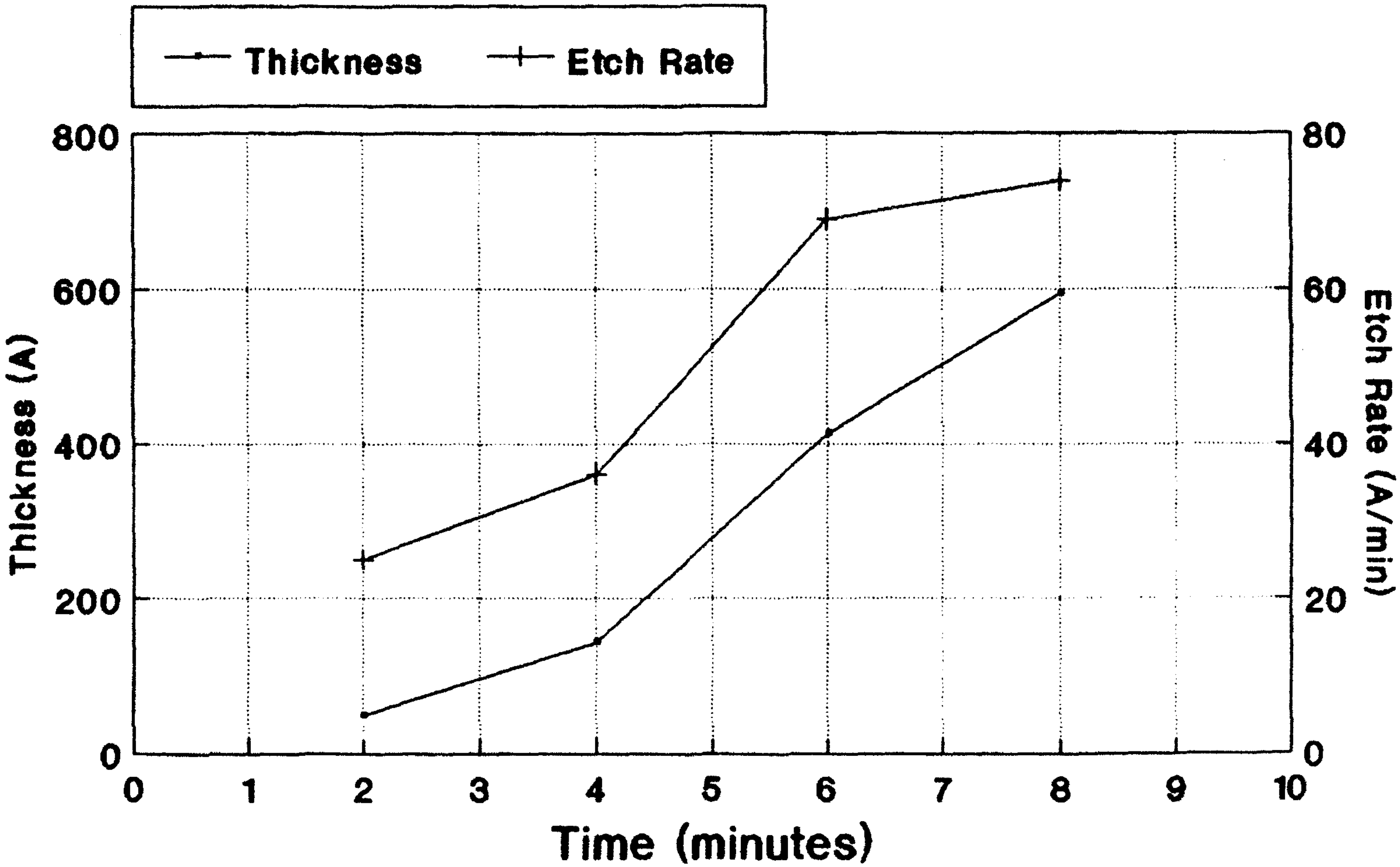


Figure 8. Etch Rate vs. Duration Study

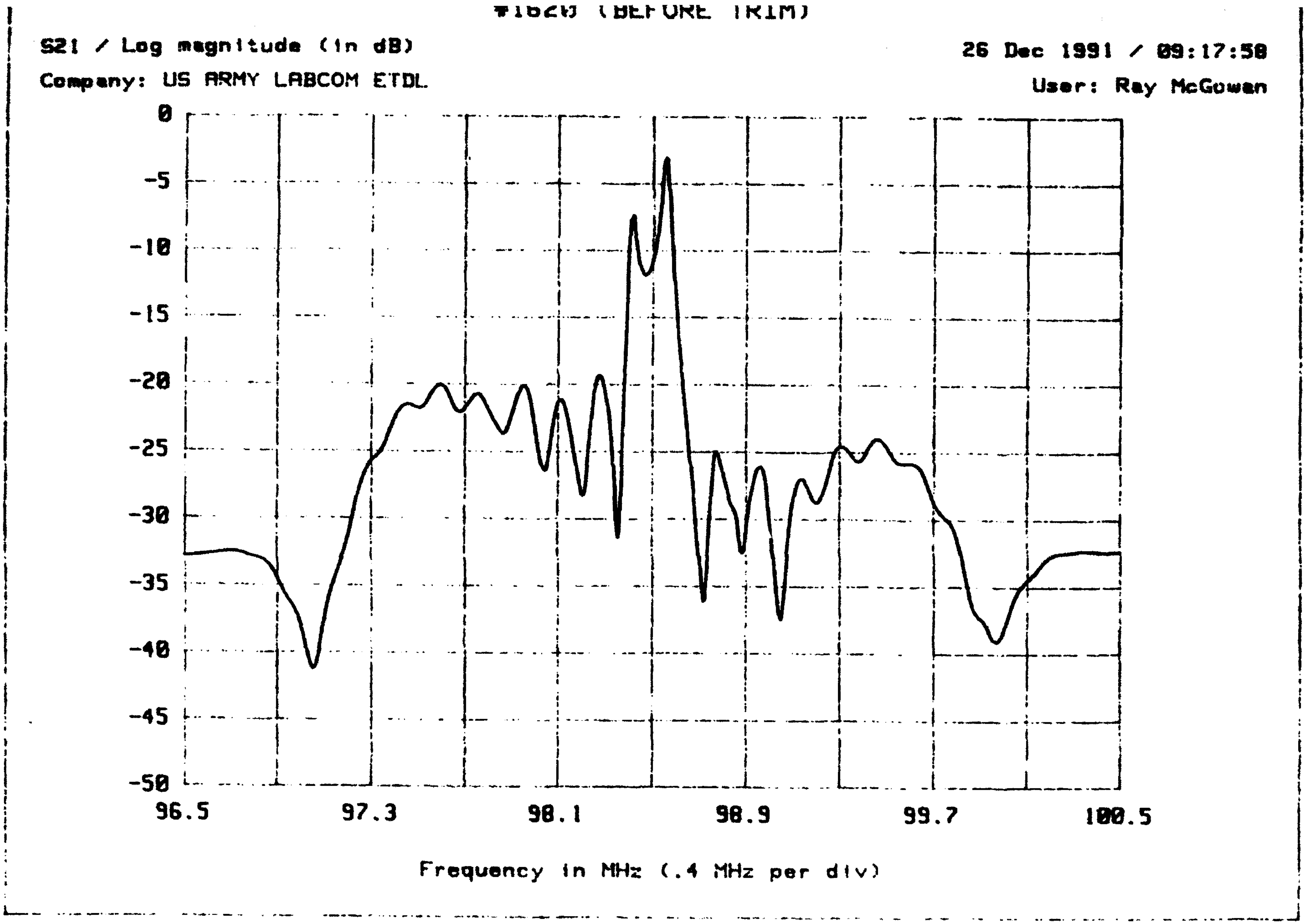


Figure 9. $S_{21,mag}$ of Resonator Before Trim, 4 MHz Sweep

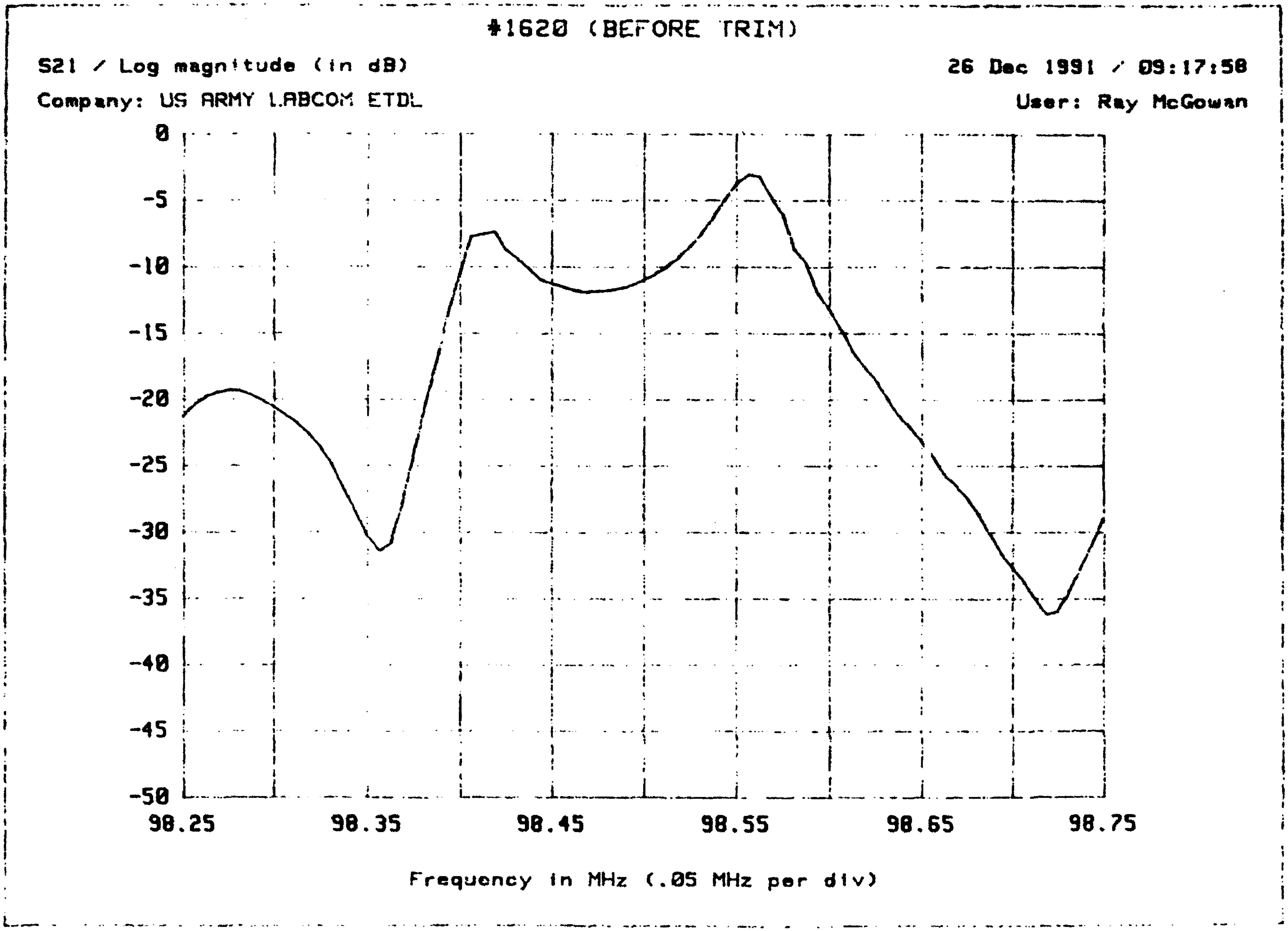


Figure 10. $S_{21,mag}$ of Resonator Before Trim, 500 kHz Sweep

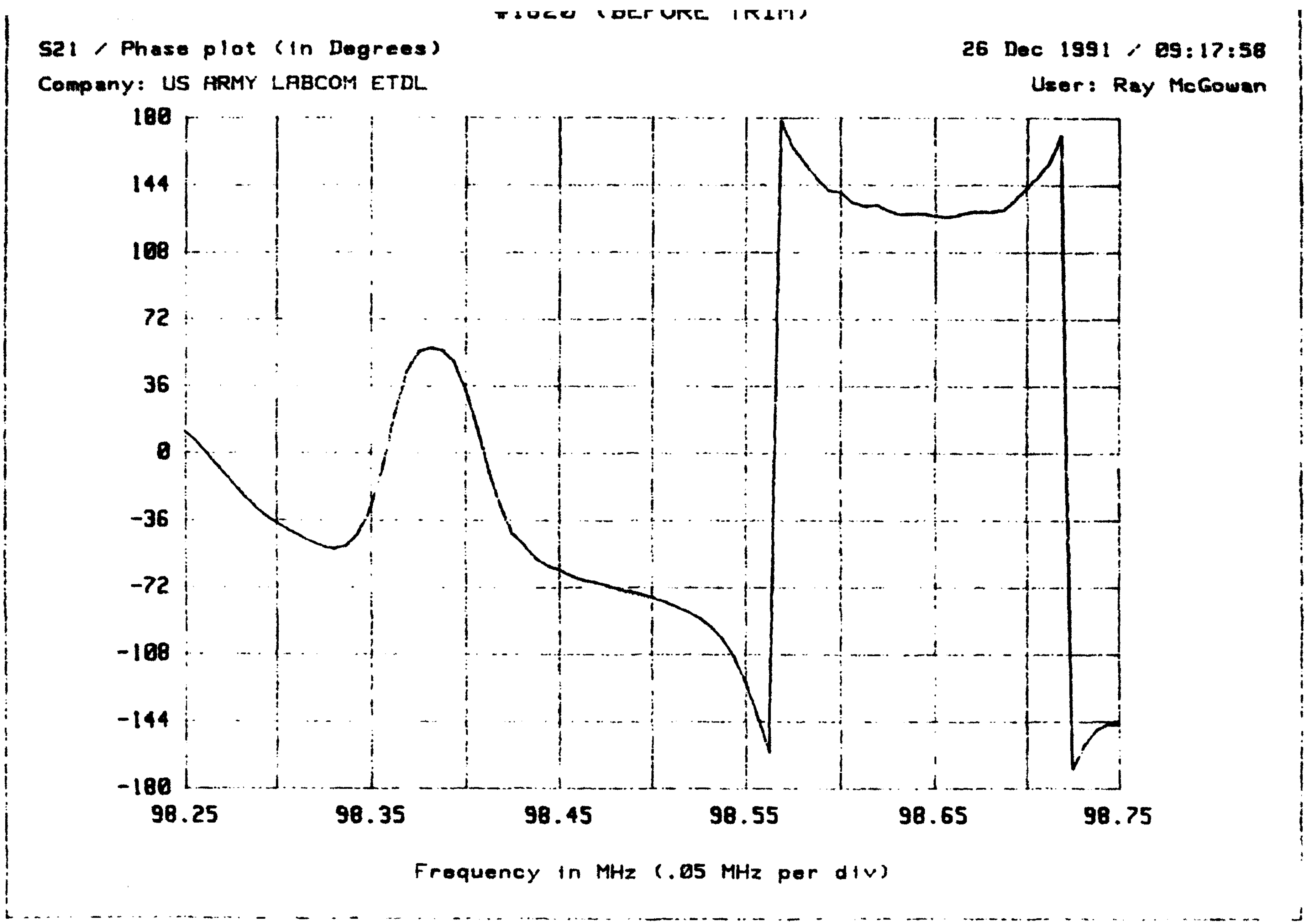


Figure 11. $S_{21,\,phase}$ of Resonator Before Trim, 500 kHz Sweep

```
Measured Resonator Parameters

Date        : 26 Dec 1991       Temperature : 25 C
Time        : 09:39:37          Amplitude   : -9.999 dBm
Device ID   :                   Load Cap.     30 pF
Equ. Ckt.   : Two Port
Power Set   : Iterate

    fs=   98 562 561.512 Hz
    R1=   30.827 Ohms
    L1=   .97638 mHy
    C1=   2.671 fF
    Q=    19614
    C0=   0 pF
    C13=  0 pF
    C23=  0 pF
    G0=   0 m mhos
    G13=  1.171 m mhos
    G23=  1.153 m mhos
    fr=   98 561 963.163 Hz
    Rr=   27.222 Ohms
    fl=   98 566 948.435 Hz
    Rl=   30.827 Ohms
    r=    0
    M=    0
    Ts=   -146.231 Hz/pF
    S21 Max=          -3.127  dB
    S21 Max Freq=   98 562 694.158 Hz
    S21 Max Phase=  -164.279  deg.
    Ql=   12133
```

**Figure 12. Resonator Parameters Before Trim**

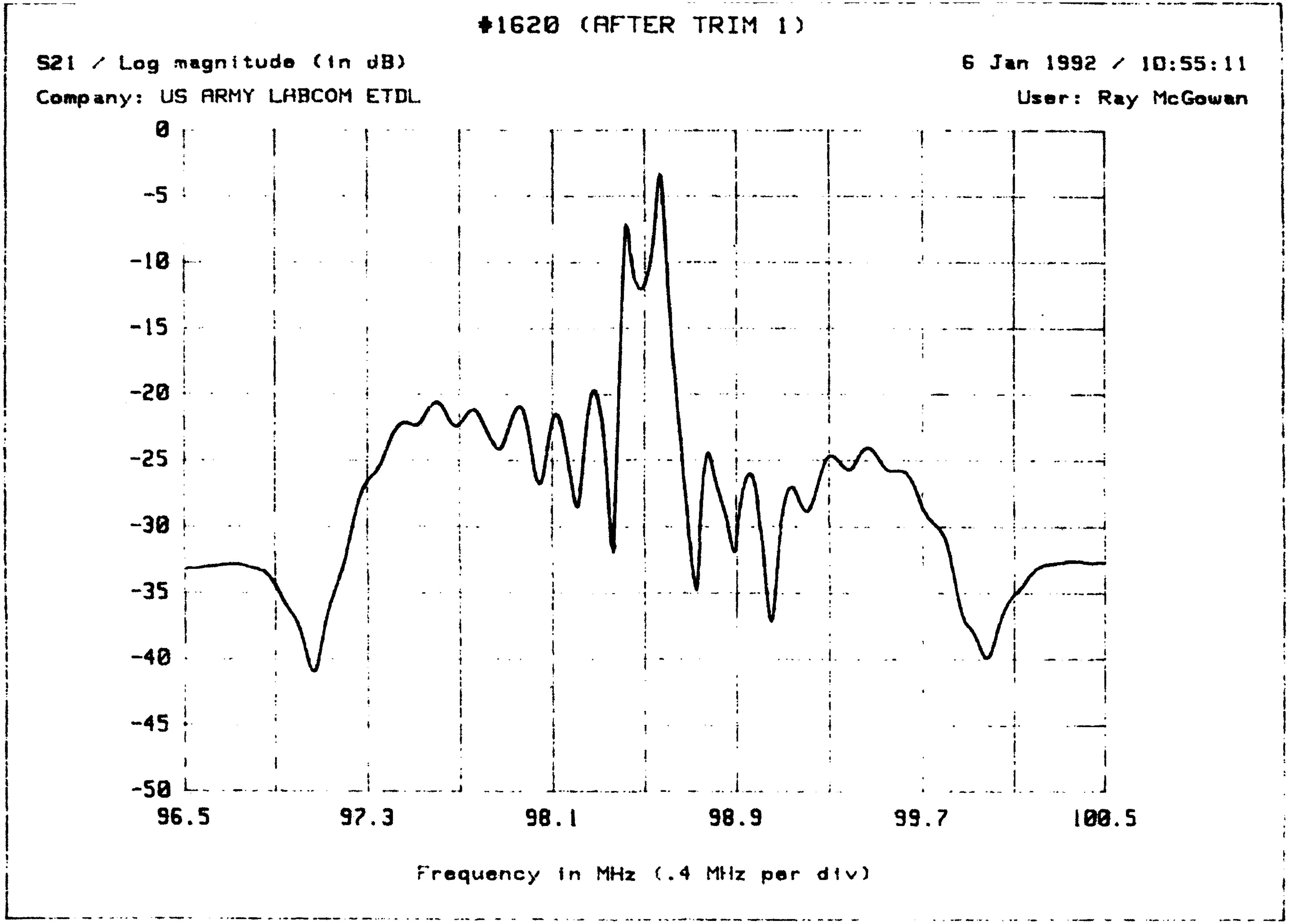


Figure 13. $S_{21,mag}$ of Resonator After Trim 1; 4 MHz Sweep

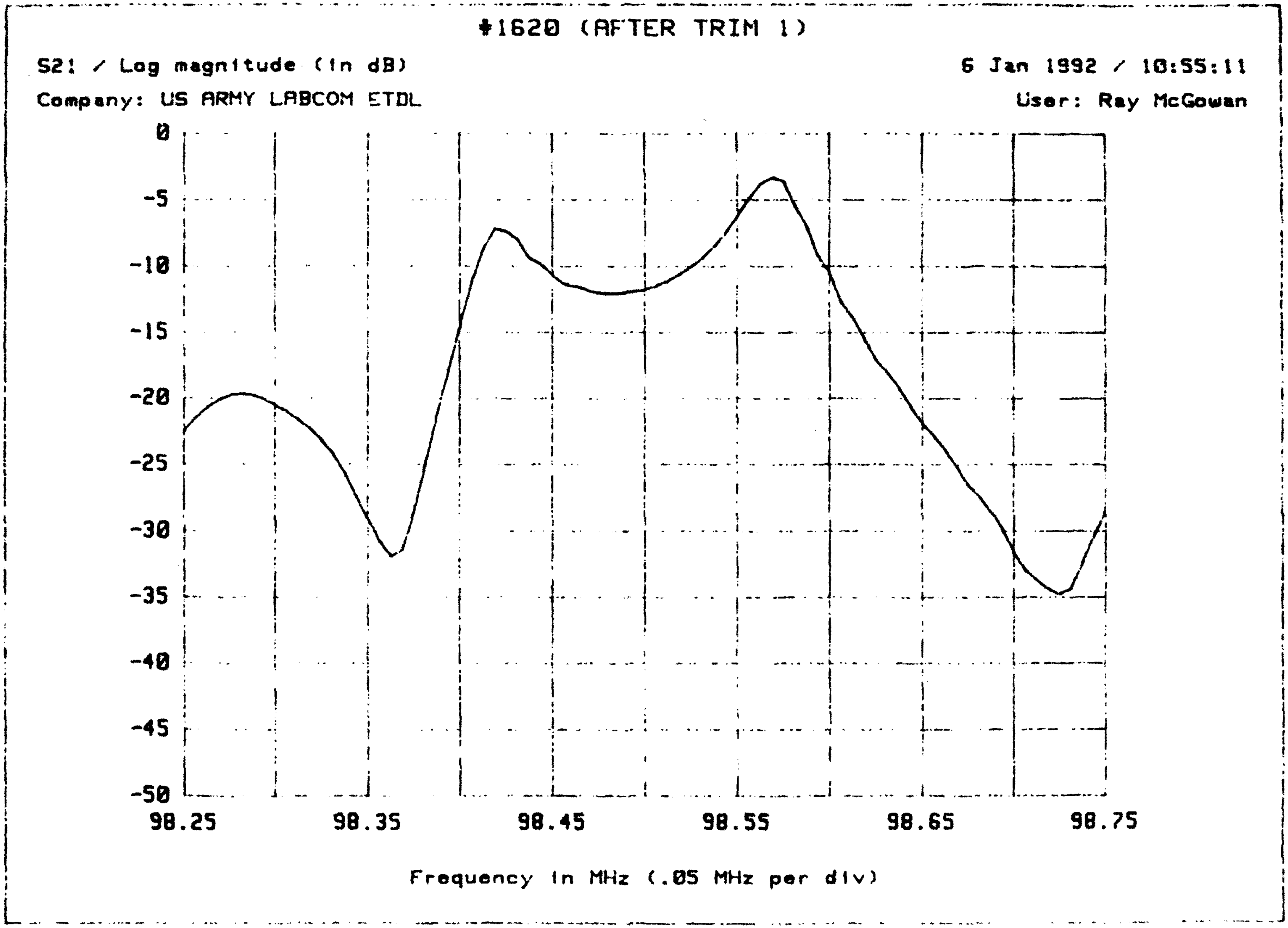


Figure 14. $S_{21,mag}$ of Resonator After Trim 1; 500 kHz Sweep

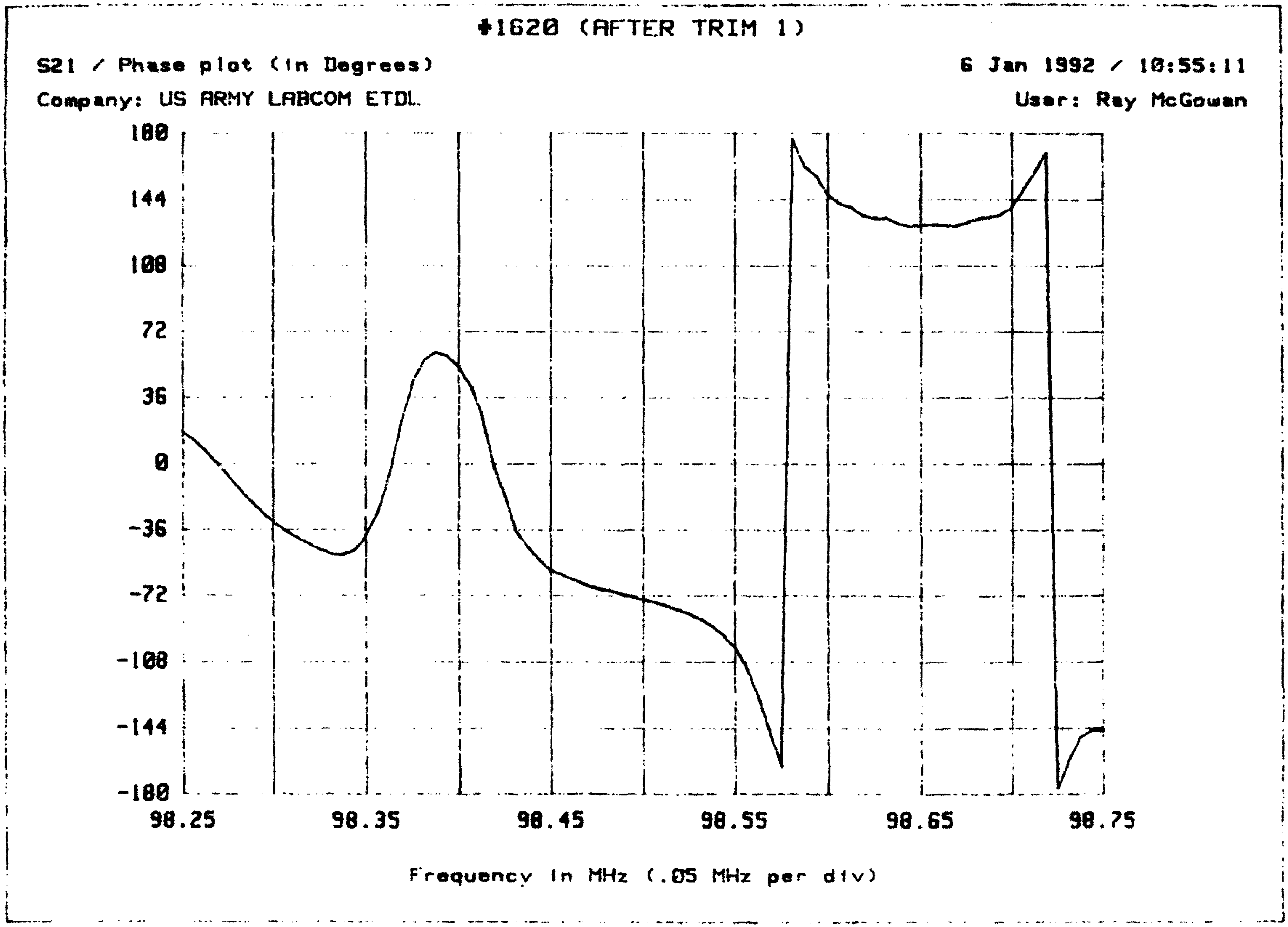


Figure 15. $S_{21,\text{phase}}$ of Resonator After Trim 1; 500 kHz Sweep

Measured Resonator Parameters

```
Date         :  6 Jan 1992        Temperature : 25 C
Time         : 11:19:46           Amplitude   : -10 dBm
Device ID    :                    Load Cap.     30 pF
Equ. Ckt.    : Two Port
Power Set    : Iterate

              fs=   98 573 730.465 Hz
              R1=   38.272 Ohms
              L1=   1.056 mHy
              C1=   2.47 fF
              Q=    17081
              C0=   0 pF
              C13=  0 pF
              C23=  0 pF
              G0=   0 m mhos
              G13=  1.248 m mhos
              G23=  1.337 m mhos
              fr=   98 572 789.984 Hz
              Rr=   32.355 Ohms
              fl=   98 577 787.995 Hz
              Rl=   38.272 Ohms
              r=    0
              M=    0
              Ts=   -135.251 Hz/pF
              S21 Max=          -3.5   dB
              S21 Max Freq=  98 574 194.394 Hz
              S21 Max Phase= -164.025  deg.
              Ql=   9675
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**Figure 16. Resonator Parameters After Trim 1**

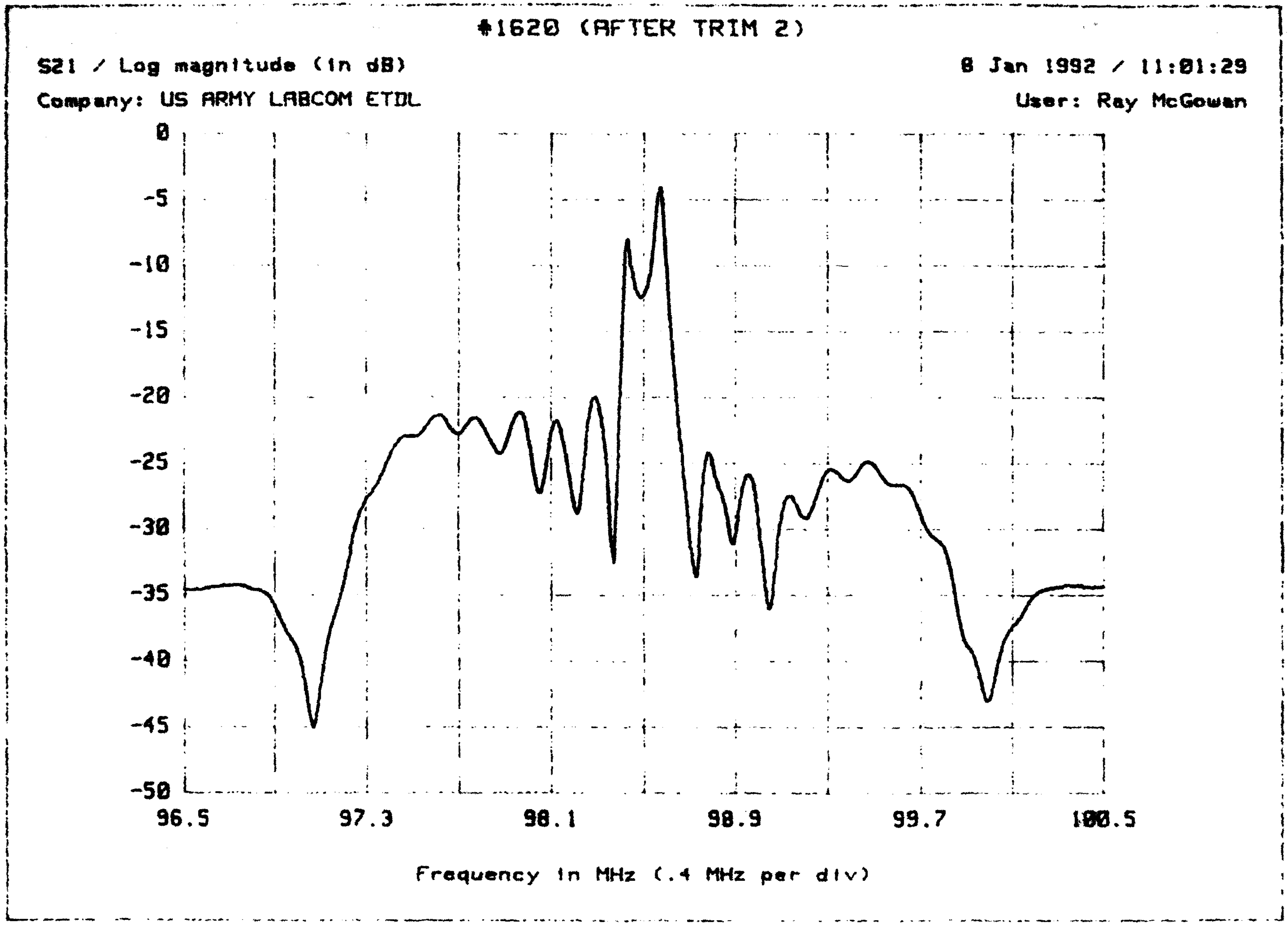


Figure 17. $S_{21,mag}$ of Resonator After Trim 2; 4 MHz Sweep

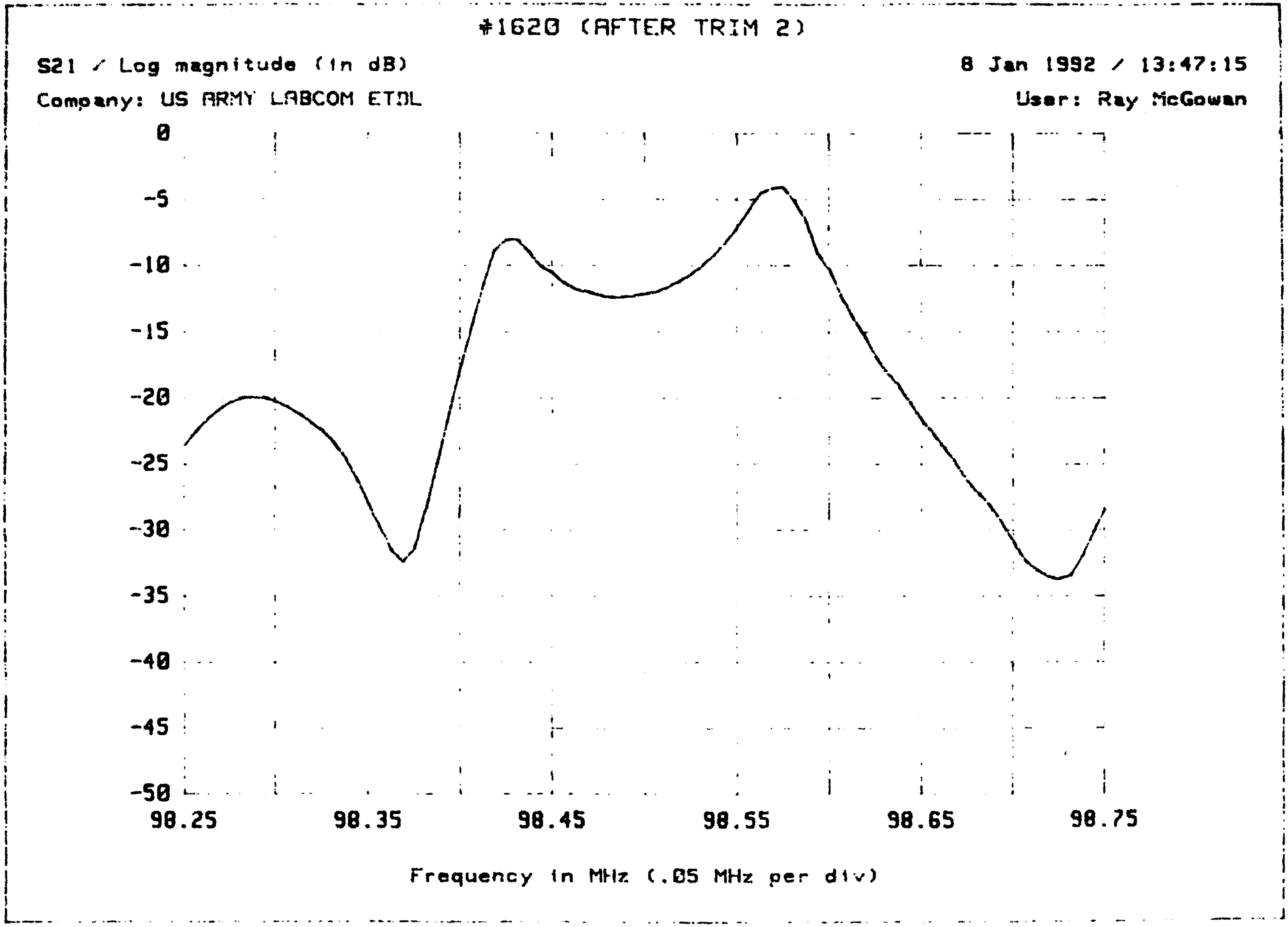


Figure 18. $S_{21,mag}$ of Resonator After Trim 2; 500 kHz Sweep

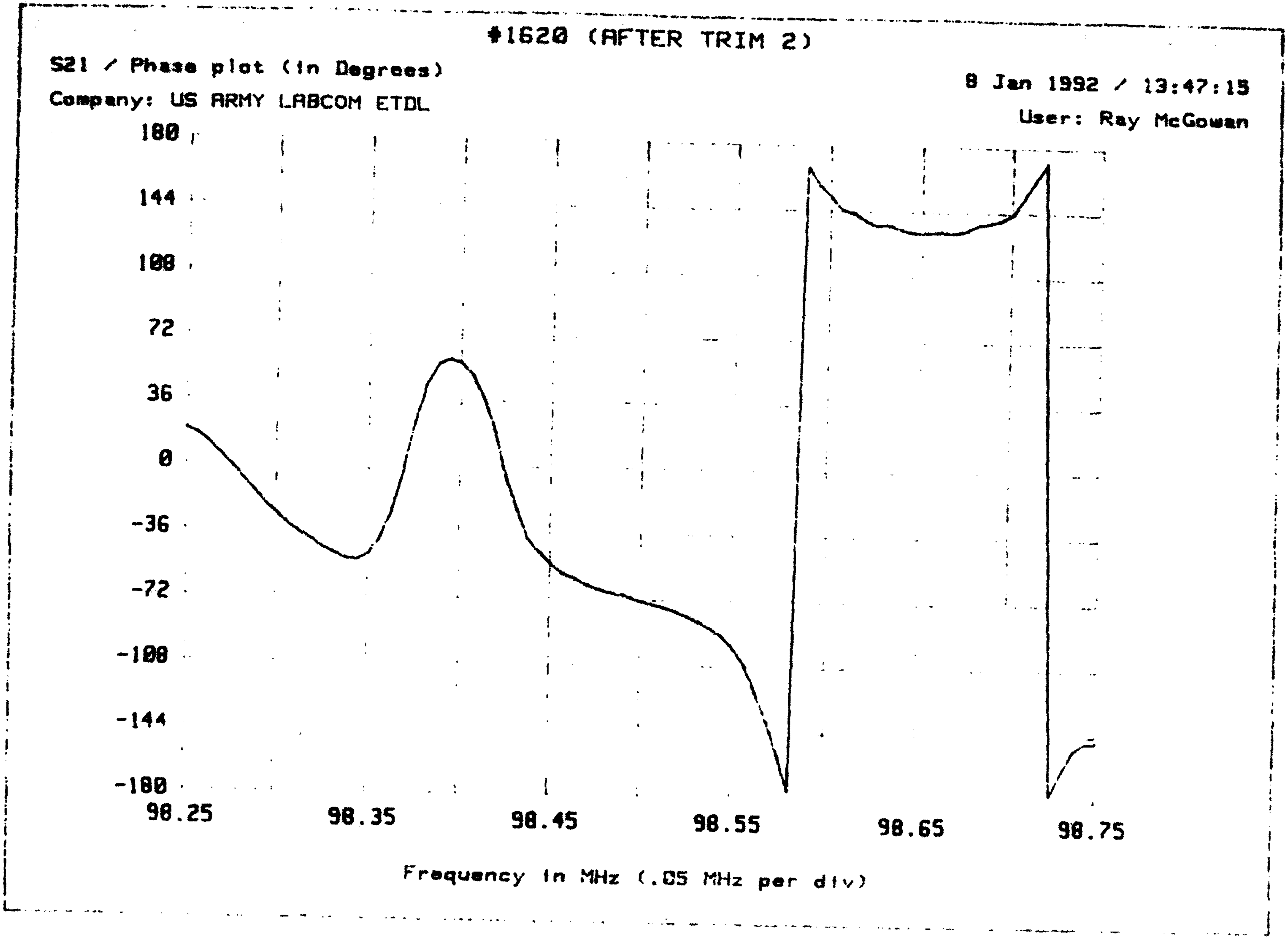


Figure 19. $S_{21, phase}$ of Resonator After Trim 2; 500 kHz Sweep

```
                Measured Resonator Parameters

Date       :  8 Jan 1992        Temperature : 25 C
Time       : 14:04:59           Amplitude   : -9.999 dBm
Device ID  :                    Load Cap.    30 pF
Equ. Ckt.  : Two Port
Power Set  : Iterate

            fs=   98 575 798.092 Hz
            R1=   43.769 Ohms
            L1=   .89681 mHy
            C1=   2.907 fF
            Q=    12691
            C0=   0 pF
            C13=  0 pF
            C23=  0 pF
            G0=   0 m mhos
            G13=  1.381 m mhos
            G23=  1.26 m mhos
            fr=   98 575 819.931 Hz
            Rr=   38.148 Ohms
            fl=   98 580 573.578 Hz
            Rl=   43.769 Ohms
            r=    0
            M=    0
            Ts=   -159.183 Hz/pF
            S21 Max=         -4.044   dB
            S21 Max Freq=  98 575 931.593 Hz
            S21 Max Phase= -160.423   deg.
            Ql=   6767
```

**Figure 20. Resonator Parameters After Trim 2**

Table 1. Etch Rate Data for Various Concentrations

| Concentration ($H_2O$:Al Etch) | Trial 1 (Å/min) | Trial 2 (Å/min) | Trial 3 (Å/min) | Average Etch Rate (Å/min) |
|---|---|---|---|---|
| 2:1 | 250 | 233 | 225 | 236 ± 13 |
| 5:1 | 150 | 138 | 117 | 134 ± 17 |
| 9.1:1* | 25 | 25 | 25 | 25 |

* 2-minute etch time was required for measurable thickness

Table 2. Etch Rate vs. Duration Data

| Etch Time (min) | $t_{REF1}$ (Å) | $t_{REF2}$ (Å) | $t_{REF3}$ (Å) | $t_{REF4}$ (Å) | $t_{AVG}$ (Å) | Etch Rate (Å/min) |
|---|---|---|---|---|---|---|
| 2 | 25 | 125 | 0 | 50 | 50 | 25 |
| 4 | 200 | 50 | 150 | 175 | 144 | 36 |
| 6 | 400 | 350 | 500 | 400 | 412 | 69 |
| 8 | 650 | 650 | 525 | 550 | 594 | 74 |

**Table 3. Aluminum Profile of the SAW Resonator**

| | t1 (Å) | t2 (Å) | t3 (Å) | t4 (Å) | $t_{avg}$ |
|---|---|---|---|---|---|
| Initial | 2900 | 2950 | 3000 | 2950 | 2950 ± 41 |
| Etch 1 (1 min) | 2600 | 2600 | 2650 | 2600 | 2613 ± 25 |
| Etch 2 (2 min) | 2500 | 2550 | 2600 | 2550 | 2550 ± 41 |

Table 4. Summary of the Resonator Characteristics

| | Before Trim | After Trim 1 | After Trim 2 | 0-1 | 1-2 |
|---|---|---|---|---|---|
| $f_s$ (Hz) | 98,562,561 | 98,573,730 | 98,575,798 | +11,169 | +2,068 |
| $f_{g-}$ (Hz) | 98,356,250 | 98,363,888 | 98,368,750 | +7,638 | +4,862 |
| $f_{g+}$ (Hz) | 98,718,056 | 98,725,000 | 98,725,000 | +6,944 | 0 |
| $f_{g,avg}$ (Hz) | 98,537,153 | 98,544,444 | 98,546,875 | +7,291 | +2,431 |
| RBW (Hz) | 361,805 | 361,112 | 356,250 | -693 | -4,862 |
| $f_{long}$ (Hz) | 141,667 | 147,222 | 145,833 | +5,555 | -1,389 |
| $f_{S21,max}$ (Hz) | 98,562,694 | 98,574,194 | 98,575,931 | +11,500 | +1,737 |
| $\|S_{21}\|_{max}$ (dB) | -3.130 | -3.500 | -4.040 | -0.370 | -0.540 |
| $t_{Al}$ (Å) | 2,950 | 2,613 | 2,550 | -338 | -63 |
| $r_{cal}$ | 0.002883 | 0.002878 | 0.002839 | -0.000005 | -0.000039 |
| $R_1$ (Ω) | 30.83 | 38.27 | 43.77 | +7.44 | +5.50 |
| $Q_l$ | 12,133 | 9,675 | 6,767 | -2,458 | -2,908 |
| $Q_u$ | 19,614 | 17,081 | 12,691 | -2,533 | -4,390 |
| Etch Time (min) | - | - | - | 6.0 | 2.0 |
| Etch Rate (Å/min) | - | - | - | 56.3 | 31.5 |
| Trim Rate (Hz/Å) | - | - | - | +33.04 | +32.82 |

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